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ABSTRACT

Indoor radon concentrations, measured in 58 houses over a four to five month period during the winter and spring of 1981-1982, varied from 0.1 to 16 pCi l^{-1} (4-590 Bq m^{-3}). Average infiltration rates were determined for each house over the same period, based on a measurement of the effective leakage area and an infiltration model, and found to range from 0.2 to 2.2 air changes per hour (hr^{-1}). Indoor radon concentrations correlated poorly with infiltration rates for houses within each city as well as for the entire sample. Differences in radon entry rates among houses thus appear to be more important than differences in infiltration rates in determining whether a house has high indoor radon levels, consistent with previous indications from grab-sample measurements. Radon entry rates and indoor radon concentrations were generally higher in houses in Fargo ND and Colorado Springs CO than in houses in Portland ME and Charleston NC.

Keywords: radon, infiltration, indoor air quality, pollutant source strength

INTRODUCTION

Exposure to the radioactive progeny of radon-222 indoors is a large component of the naturally-occurring radiation dose to the public (UNSCEAR82). Indoor radon concentrations are known to vary widely and at the higher concentrations observed in residences, occupant exposure can exceed the occupational limit of 4 working level months (WLM) per year (e.g., He82, Sa82); these exposures have a high probability of causing a significant increase in the risk of lung cancer to the population exposed (Ne83a).

Radon concentration inside a dwelling is determined by the rates of entry and removal. Radon enters houses via diffusion and pressure-driven flow after emanating from soil and rock near the building foundation and from building materials; it may also enter with tap water originating from wells and springs. The primary removal mechanism is ventilation which is comprised of infiltration (i.e., the uncontrolled leakage of air through cracks in the building envelope), natural ventilation through open doors and windows, and mechanical ventilation. Infiltration is the dominant ventilation component in most U.S. housing during the heating season. With the interest in lowering infiltration rates to reduce energy use in buildings it is important to understand the relative importance of ventilation in determining indoor radon concentration.

For a specific house, according to a simple mass-balance model, the indoor radon concentration varies in inverse proportion to the ventilation rate, assuming the rate of radon entry is uncorrelated with ventilation and that the outdoor radon concentration is much smaller than that indoors. In this case, simultaneously measuring the ventilation rate and the radon concentration yields the radon entry rate, a characteristic of the house and the local source materials. This inverse relationship was observed to hold in one two-week study in a low-infiltration house in which a balanced mechanical ventilation system was used to vary the ventilation rate (Na81). In another study, however, the indoor radon concentration was found to not vary as greatly with changes in ventilation as predicted by the simple model (Na83). In that case, infiltration was the dominant ventilation mechanism and it was postulated that the same forces that drive infiltration also affected the rate radon entered the house from the soil. In such cases, even though the radon entry rate varies over time, an indication of the average value can still be determined from simultaneous long-term measurements of ventilation rate and radon concentration. However, instead of simply being a characteristic of the house and local source materials, the average entry rate would also depend on the driving forces.

For a set of houses, if the radon entry rates are comparable and uncorrelated with ventilation, then the average air-exchange rate will be a useful predictor of the average indoor radon concentration, i.e., houses with lower air-exchange rates will have higher radon concentrations and vice versa. In a study employing single grab-sample measurements, Nero et al. (Ne83b) found no correlation between radon concentration and ventilation rate either among the 100 houses studied or within any of the three subsets. Because the range of indoor radon concentrations substantially exceeded the range of ventilation, they concluded that the radon entry rate, rather than the air-exchange rate, was the dominant factor in determining the indoor radon level.

Because of the variability over time of indoor radon concentrations and ventilation rates, it is not clear that the results observed in Nero et al. apply to the time-averaged values. Since the health risk due to exposure to radon progeny is associated with cumulative exposure, the time-averaged values are of primary interest. In the present study average radon concentrations and infiltration rates for a four to five month period were determined for a sample of 58 houses located in four U.S. cities. From these data radon entry rates are calculated and the distributions of these parameters for the four cities are discussed.

EXPERIMENTAL

Building Selection

The data were collected as part of a study that examined the effects of different combinations of weatherization and energy-conserving systems on energy consumption in low-income housing (Cr82). Twelve cities were chosen to represent different climatic zones of the United States; in four of these cities indoor radon concentrations were measured. Individual homes within each city were selected for the energy-conservation study from files of households eligible for fuel subsidies or weatherization grants. The selection process attempted to obtain variability in building age and construction type within the sample set for each city; individual houses were required to have a simple geometry and be in a good state of repair.

Infiltration Rates

A model was used to calculate infiltration rates (Gr82), based on measurements following weatherization of the "effective leakage area". In addition to leakage area, the model requires information about the geometry of the house and the degree of shielding due to terrain and nearby obstructions, and data for outdoor and indoor temperatures and wind speed. The geometry and shielding information were collected by field contractors during the study; weather data were obtained from National Weather Service stations in each city. Indoor temperature was assumed to be 22°C.

Effective leakage area is determined by measuring flow across the building envelope for a range of pressures induced by a large fan. In this study houses were typically depressurized over a range of 10-50 Pa, and the data fit to the function

$$Q(\Delta P) = C\ \Delta P^{n} \tag{1}$$

where ΔP is the measured pressure drop across the shell of the house, Q is the air flow through the fan, calculated from the measured fan speed and ΔP using a fan-response curve, and C and n are coefficients determined by regression analysis of the data. The fans used in each city were similar and assumed to have identical pressure-flow response curves which we determined by calibrating one fan at our laboratory.

The leakage area, A_o, is calculated as

$$A_o = Q(\Delta P_r) \left(\frac{2\Delta P_r}{\rho}\right)^{-\frac{1}{2}} \tag{2}$$

where ρ is the air density and $\Delta P_r = 4$ Pa is the reference pressure used in the model.

The model treats infiltration as a combination of two uncorrelated, pressure-driven flows, each proportional to leakage area:

$$Q_{stack} = A_o\ f_s\ (\Delta T)^{\frac{1}{2}}, \tag{3}$$

and

$$Q_{wind} = A_o f_w v, \tag{4}$$

where ΔT is the indoor-outdoor temperature difference and v is the wind speed. The coefficients f_s and f_w are the stack and wind parameters, respectively; they account for the geometry and shielding of the house and the height of the wind measurement, relative to that of the house.

In deriving the model, the researchers assumed that flow across the building envelope is proportional to the square root of the induced pressure and that the pressure effects are additive, so the total infiltration is

$$Q_{total} = (Q_{stack}^2 + Q_{wind}^2)^{1/2}. \tag{5}$$

Dividing the total flow rate by the volume of the house gives the infiltration rate, λ , taken here to be the total ventilation rate of the house, as natural and mechanical ventilation rates are typically small during the heating season.

Infiltration rates were averaged in three ways, in each case using the period of radon measurement for the given house. First, daily average infiltration rates, λ_i, were determined from daily average weather data and from these the arithmetic-mean infiltration rate was computed. The second approach, appropriate assuming the radon entry rate is independent of the infiltration rate, averaged the inverse of the daily average:

$$\lambda^* = \left(\frac{1}{n} \sum_i \frac{1}{\lambda_i}\right)^{-1} , \tag{6}$$

where n is the number of days for the radon measurement. The third approach averaged weather data first for the entire four to five month period, then calculated a single infiltration rate. The arithmetic means of the daily rates differed from the rates derived from averaged weather-data by less than 2%, and the values of λ^* were only 1-5% smaller so that the choice of averaging technique makes little difference. The values reported here are arithmetic means of daily average infiltration rates.

Uncertainties in infiltration rate determination arise primarily from the errors in measuring leakage area, in estimating shielding coefficients, and from the simplifications implicit in the infiltration model. None of these contributions are easily estimated in a rigorous way; direct comparisons of measured infiltration and predictions from this model have shown that the relative standard deviation in the prediction ranges from 20 to 35% depending on the length of the averaging period (Gr82, Li83).

Radon Concentrations

Time-averaged radon concentrations were made using Track-Etch® detectors (Terradex Corp., Type B). In each house one detector was placed in the living area for four to five months between November 1981 and May 1982. At a few houses in three of the cities, outdoor radon concentration was measured by hanging a detector from the porch roof or from the roof eaves. Three detectors, ordered at the same time as the others, were not deployed, but were analyzed as blanks. Their average cumulative exposure, 27 +/- 9 pCi l^{-1} day (1000 +/- 330 Bq m^{-3} day), was subtracted from each indoor and outdoor measurement.

Using the approach of Alter and Fleischer (Al81), the relative standard deviation in individual radon concentration measurements is estimated to range from 38% for 1 pCi l^{-1} (37 Bq m^{-3}) to 27% for 10 pCi l^{-1} (370 Bq m^{-3}). In the former case the contribution to uncertainty due to counting a small number of tracks (from 1.15 mm^2 of detector area) is comparable to that due to the variance in detector response. In the latter case, and for any greater exposure, uncertainty is dominated by detector-response variance.

RESULTS AND DISCUSSION

Measurement results for each of the 58 houses are presented in Table 1. These data show clear differences among the four cities in indoor radon concentration: while none of the houses in Charleston or Portland had concentrations in excess of 5 pCi l^{-1} (175 Bq m^{-3}), two of 16 houses in Colorado Springs and seven of 11 houses in Fargo exceeded this value. In the three houses with the highest concentrations, each located in Fargo, the annual exposure to occupants may exceed 4 WLM/yr, the occupational limit. It is striking that the infiltration rates for these three houses are not low: they vary from 0.4 to 1.3 hr^{-1}, spanning what is considered to be the normal range.

The data are summarized by city and for the entire sample in Table 2. The nature of the distribution of radon concentrations and infiltration rates could not be determined on a city-by-city basis because of the small number of measurements in each. However, considering the entire data set, a chi-square goodness-of-fit test (Hi80) showed that normal distributions could be rejected with 99% confidence, while log-normal distributions provided reasonable fits, particularly for radon concentration. Hence, in Table 2, geometric means and geometric standard deviations are reported.

The hypothesis that the true mean values both for radon concentration and for infiltration rate are equal was tested for each pair of cities

(Hi80). For radon concentration, this hypothesis can be rejected with 99.9% confidence for all pairs of cities except Charleston and Portland. For infiltration rate, on the other hand, this hypothesis cannot be rejected with even 99% confidence for any pair of cities except Colorado Springs and Portland. Thus, the order-of-magnitude higher mean radon concentration in Fargo relative to that in Portland and in Charleston cannot be attributed to sampling uncertainty. Neither can it be attributed to differences in mean infiltration rates, at least in the context of the simple mass-balance model. Rather, it is due primarily to differences in the rates of radon entry into houses between these cities. Furthermore, considering the entire data set, the geometric standard deviation in the radon entry rate greatly exceeds that in infiltration rate, and is thus the dominant factor in determining the breadth of the range of radon concentrations in this sample.

This point is illustrated perhaps more clearly in Figure 1. If radon entry rates among the houses were comparable, for concentrations much greater than the outdoor value the points would tend to lie along a straight line with a downward slope of 45 degrees. Instead there is no apparent correlation between indoor radon concentrations and infiltration rate either within the entire data set or within a single city.

The measurements of outdoor concentrations show surprisingly high values in Colorado Springs and Fargo with respect to the range for continental air of 0.1 - 0.4 pCi l^{-1} (4-15 Bq m^{-3}) cited by Gesell (Ge83). This suggests the possibility of a bias in the concentration measurements resulting perhaps from inadvertent exposure of certain of the detectors during the lengthy interval (1.5 yrs) between their purchase and analysis.

Nevertheless, this bias would be additive and therefore unlikely to account for the higher concentrations observed.

CONCLUSION

Time-averaged indoor radon concentrations in this four-city sample were more broadly distributed than the corresponding infiltration rates. This observation leads to the same conclusion obtained from a grab-sample survey (Ne83b): the variability in radon entry rate among houses plays a greater role than infiltration in determining indoor radon levels. Also consistent with the results of other studies of indoor radon is the observation that in the United States and Canada, at least, high indoor radon concentrations are rarely observed in certain regions, while in other areas, even though many of the houses may have low to moderate concentrations, a significant fraction have indoor radon levels that may be considered excessive. Thus far these regions have been identified incidentally; improved knowledge of radon transport processes and the influence of geologic factors on radon source potentials is likely to aid the systematic identification of such regions.

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TABLE 1

House	Foundation Type[a]	Volume (m^3)	Effective Leakage Area (cm^2)	Infiltration Rate (hr^{-1})	Radon Concentration ($pCi\ l^{-1}$)[b]	Radon Entry Rate ($pci\ l^{-1}\ hr^{-1}$)[b]
	CHARLESTON, SC					
CHA 02	CS	304	656	0.5	0.2	0.1
CHA 03	S	246	362	0.3	0.7	0.2
CHA 08	S	246	1100	1.1	0.3	0.3
CHA 09	S	246	861	0.9	1.6	1.4
CHA 16	S	274	1281	1.1	0.7	0.7
CHA 18	CS	254	356	0.3	0.9	0.3
CHA 19	CS	185	1302	1.6	0.1	0.2
CHA 20	CS	292	1100	0.9	0.2	0.2
CHA 21	CS	266	424	0.4	0.5	0.2
CHA 22	CS	208	1019	1.2	0.4	0.4
CHA 23	CS	310	564	0.5	1.0	0.4
CHA 24	CS	140	784	1.4	1.0	1.4
CHA 25	CS	153	1368	2.2	0.6	1.2
CHA 27	CS	213	915	1.1	0.1	0.2
CHA 33	CS	231	852	0.9	0.5	0.4
CHA 39	CS	247	1238	1.2	0.8	1.0
CHA 42	CS	272	2308	2.1	0.8	1.6
CHA 44	CS	202	1229	1.5	0.6	1.0
CHA 47	CS	236	1230	1.3	0.3	0.4
CHA 49	CS	232	608	0.6	0.4	0.2
	COLORADO SPRINGS, CO					
CSP 11	CS	189	345	0.5	2.0	0.9
CSP 13	B,CS	123	255	0.5	1.2	0.6
CSP 14	FB	338	392	0.4	0.7	0.3
CSP 17	B,CS	115	314	0.7	5.0	3.4
CSP 20	B,CS	222	396	0.5	8.6	3.9
CSP 23	B	344	520	0.5	0.9	0.5
CSP 24	B,CS	246	594	0.6	2.6	1.5
CSP 31	FB	347	400	0.4	2.2	0.8
CSP 34	B,CS	234	1731	2.3	2.7	6.1
CSP 41	CS	147	276	0.5	2.1	1.0
CSP 43	FB	405	289	0.2	4.2	0.7
CSP 47	B,CS	134	530	1.0	3.3	3.2
CSP 49	CS	200	383	0.5	0.7	0.3
CSP 60	B,CS	206	743	0.9	1.4	1.2
CSP 61	CS	203	919	1.1	2.7	2.9
CSP 62	CS	197	856	1.1	0.3	0.3
	FARGO, ND					
FAR 06	B	162	159	0.3	5.2	1.5
FAR 10	B	147	183	0.4	1.1	0.4
FAR 15	B,FB	316	425	0.4	6.3	2.5
FAR 17	CS	173	535	0.9	15.8	14.2
FAR 25	B	128	219	0.5	3.0	1.5
FAR 27	B	105	736	2.2	8.1	17.9
FAR 30	B	131	359	0.9	4.2	3.6
FAR 32	B	247	202	0.3	8.1	2.0
FAR 35	CS	277	222	0.2	1.9	0.4
FAR 36	CS	117	153	0.4	15.3	5.8
FAR 37	B	144	632	1.3	14.8	19.1
	PORTLAND, ME					
POR 07	B	350	1052	0.9	0.5	0.4
POR 11	B	262	942	1.2	1.0	1.1
POR 12	B	308	914	0.9	0.4	0.3
POR 23	B	475	1032	0.7	1.7	1.1
POR 26	B,CS	329	1025	1.0	0.1	0.1
POR 28	B	470	1622	1.2	0.1	0.2
POR 30	B	477	1012	0.6	2.2	1.4
POR 40	B	390	1593	1.4	0.6	0.9
POR 41	B	134	410	0.9	0.6	0.5
POR 42	B	477	1305	1.0	0.4	0.4
POR 43	B	276	933	1.1	0.1	0.1

[a] Foundation type abbreviations: CS - crawl space, S - slab, B - basement, FB - finished basement

[b] 1 $pCi\ l^{-1} = 37\ Bq\ m^{-3}$

Table 1. Detailed measurement results for the 58 houses.

TABLE 2

City (No. of Houses)	Radon Concentration ($pCi\ l^{-1}$)[d] GM[a]	GSD[b]	Infiltration Rate (hr^{-1}) GM[a]	GSD[b]	Radon Entry Rate[c] ($pCi\ l^{-1}\ hr^{-1}$)[d] GM[a]	GSD[b]	Outdoor Radon Concentration ($pCi\ l^{-1}$)[d] Mean	(No. of Meas.)	Typical House Characteristics
Charleston, SC (20)	0.5	0.9	0.9	1.8	0.4	2.3	0.4	(9)	one floor crawl space space heaters 6 - 55 yrs old
Colorado Springs, CO (16)	1.9	2.3	0.6	1.8	1.1	2.7	1.2	(5)	split-level, 1-2 floors part crawl sp., part base. forced air heating 7 - 87 yrs old
Fargo, ND (11)	5.7	2.4	0.5	2.1	3.0	3.9	1.6	(1)	one floor basement forced air heating 21 - 76 yrs old
Portland, ME (11)	0.4	3.0	1.0	1.3	0.4	2.7	---	(0)	two floors basement forced air or water 15 - 150 yrs old
All Cities (58)	1.1	3.7	0.7	1.8	0.8	3.6			

[a] geometric mean, $GM = \exp(\frac{1}{n} \Sigma \ln(x_i))$

[b] geometric standard deviation, $GSD = \exp\left(\frac{\Sigma(\ln(x_i)-\ln(GM))^2}{n-1}\right)^{\frac{1}{2}}$

[c] calculated as the product of radon concentration and infiltration rate

[d] $1\ pCi\ l^{-1} = 37\ Bq\ m^{-3}$

Table 2. Summary of measurement results by city.

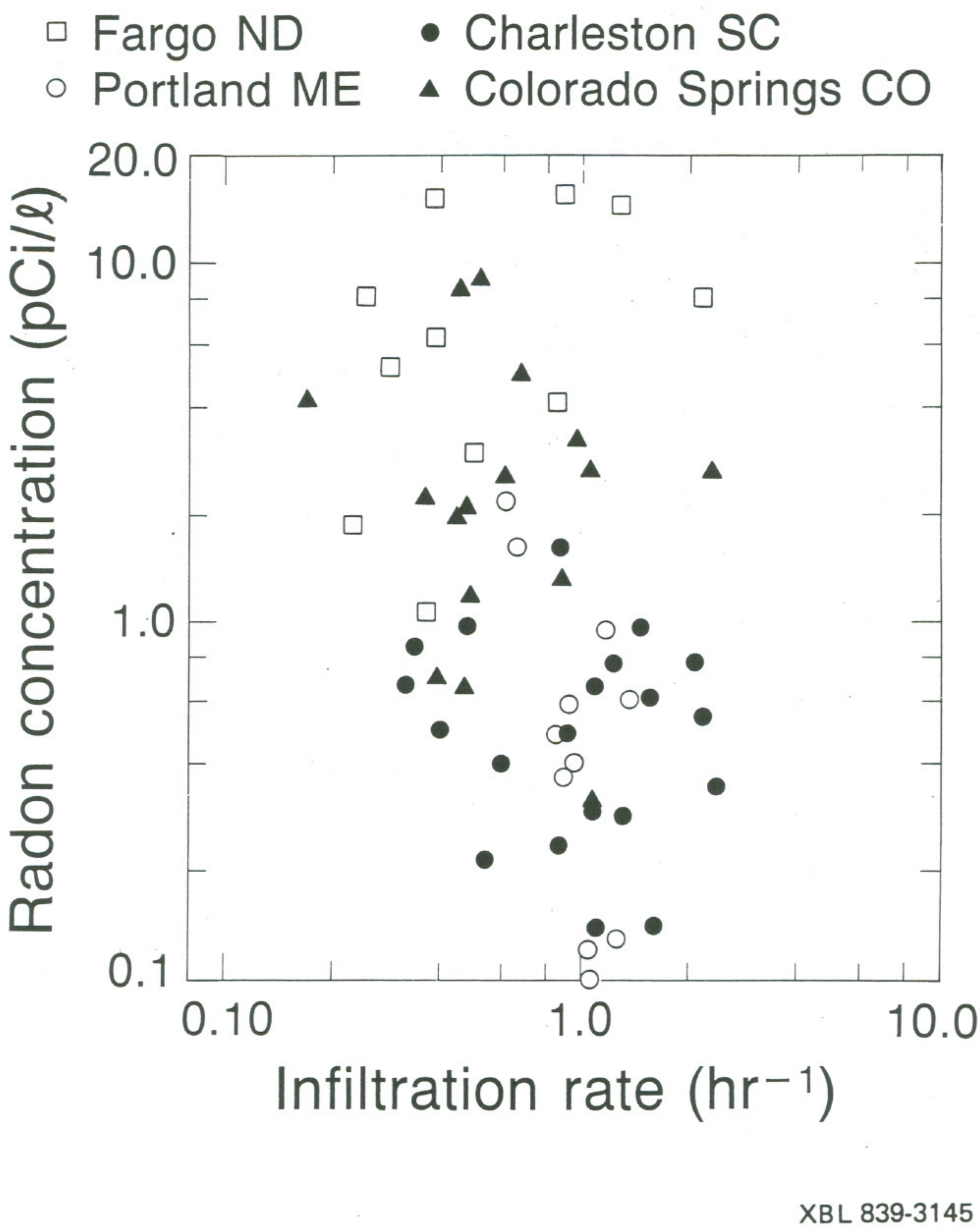

Figure 1. Scatter plot of radon concentration vs. infiltration rate for 58 houses in four cities. Measurements were made during a four to five month period between November 1981 and May 1982.